An Integrated Approach to the Recovery of Fiber, Chemicals and Energy from Fibrous Textile and Carpet Waste

Robert Evans, Carolyn Elam, and Stefan Czernik
National Renewable Energy Laboratory

(Paper not available at time of publication.)

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National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401

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(1997)

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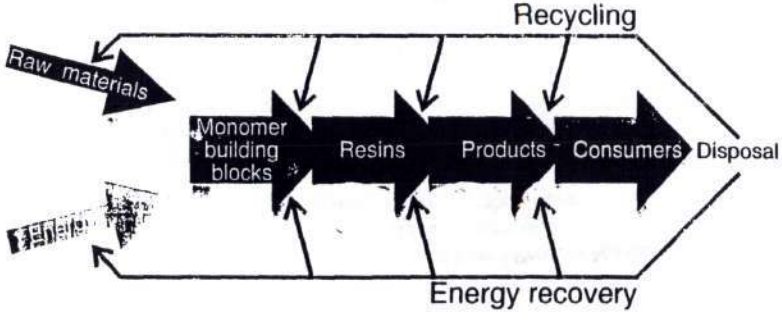
Polymers as a Resource for Industry

What is Needed?

- Completing the Life Cycle of Polymers Back to Chemicals by Linking:
  - Chemical Industry
  - Material Manufacturers
  - Municipalities
  - Consumers
- Benefits:
  - Increase the Sustainability of the Chemical Industry
  - Provide Additional Source of Chemicals
  - Provide Information for Design of Products for Recycling

Plastics in the Environment



The purer the recycle stream - the higher the value (and cost)

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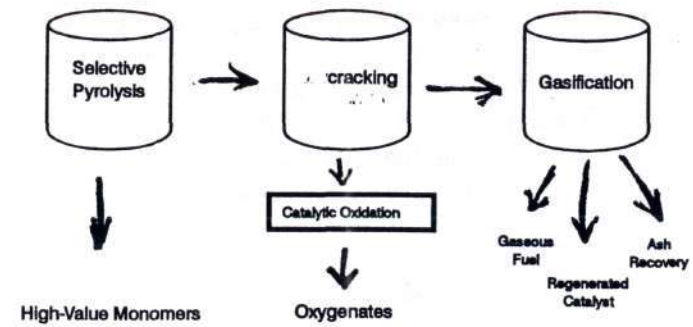
Chemical Recycling

- Mixed Polymers are Costly to Separate and Lose Performance Properties When Blended
- Recycling Back to Chemicals has the Potential to be Economical and Allow Plastics to be Truly Recyclable
- Measure the Efficiency by How Much of the Embodied Energy is Saved
- Transporting Materials fro recycling adds Costs, Which suggests Smaller Plants Near Waste Source

Flexible Chemical Processing

- Processing Facilities Convert Several Mixed Polymer Materials
  - Target Feedstocks are Sorted and Stockpiled
  - Each Type is Processed in Long Duration Runs
- Target Materials:
  - Carpets: Nylon 6, Nylon 66, PET, and Polypropylene
  - PET/Cotton Textiles
  - Polyurethanes
  - Engineering Polymer Blends
- Selective Pyrolysis is used to Recover Valuable Monomers
- Gasification is Used to Convert Organic Residue to Synthesis Gas
  - Syn Gas used on Site to make Chemicals

Thermocatalytic Recovery of High-Value Chemicals from Waste Plastics
(Flexible Chemical Processing)



Sustainability in the Chemical Industry

- from *the U. S. Chemical Industry Technology Vision 2020:*
  - "The U. S. chemical industry ... promotes sustainable development by investing in technology that protects the environment and stimulates industrial growth while balancing economic needs with financial constraints."
- Sustainability:
  - "...technological development that meets the economic and environmental needs of the present while enhancing the ability of future generations to meet their own needs."

Selective Pyrolysis

- Selective Pyrolysis: Pyrolyze One Component of a Mixture to Give one Major Product While Other Components Remain Unreacted
- Selectivity is Achieved by
  - Exploiting Differential Kinetics
  - Selective Catalytic Pyrolysis
  - Selective Reactive Pyrolysis
- NREL has Patented 8 Applications of Selective Pyrolysis
- Different Than Conventional View of Pyrolysis, Seen as Process for Converting Materials to Fuels with Low Selectivity and Value

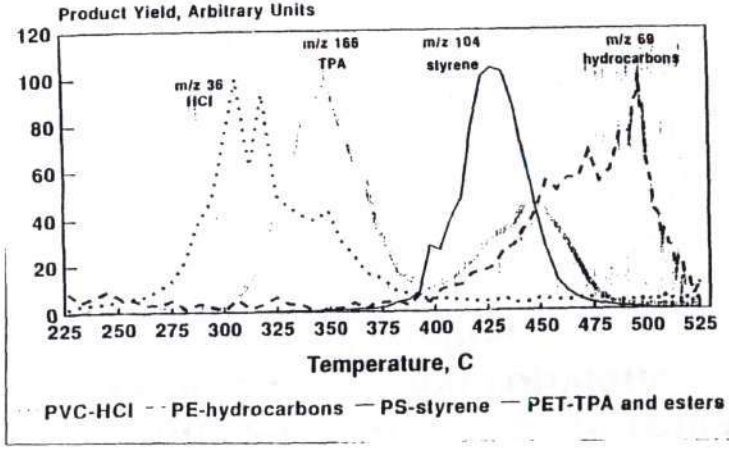
Advantages of Selective Pyrolysis Over Other Chemical Processes

- Ability to handle a variety of waste streams with the same reactor system.
- Relatively insensitive to feedstock contamination.
- Potential to recover value from 100% of the plastics in mixtures by incorporation of gasification.
- Smaller-scale operations possible and/or desirable.

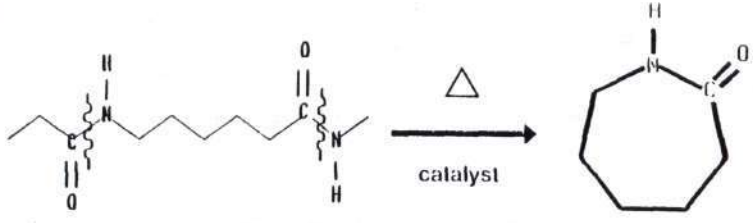
Flexible Chemical Processing What's New?

- Integration of Caprolactam and Fiber Recovery
- Alternative Reactor Design to be Tested
- Simple Purification Process Developed
- Use of Calcium Carbonate as Catalyst
- New Emphasis on Gasification.
- Recover Chemicals From PET (carpet +)

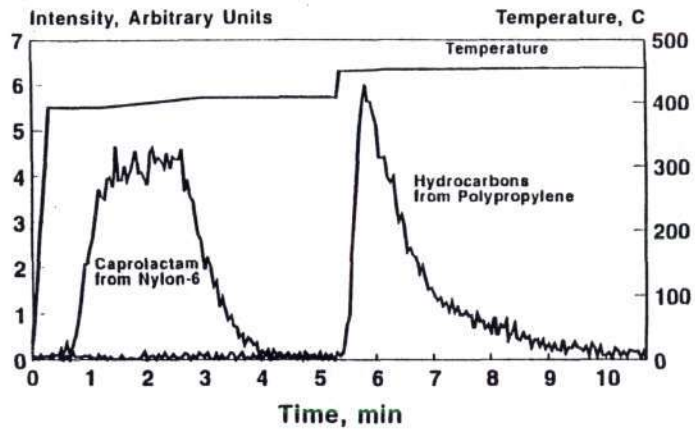
Pyrolysis of Mixed Plastics
PVC, PS, PE and PET



Nylon-6 to Caprolactam



Temperature-Programmed Pyrolysis Nylon-6 and Polypropylene with Catalyst

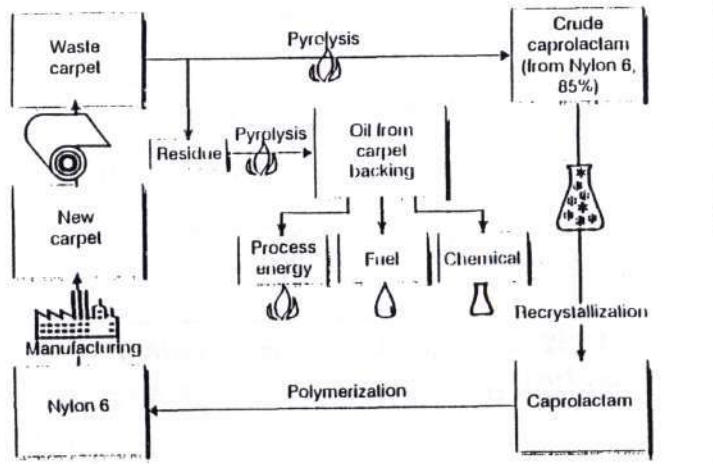


Nylon - 6 Waste Streams

Fluidized Bed Pyrolysis Research

- Four Inch Fluidized Bed Reactor Operating at Hazen Research
  - .5 kg/hr Experiments with Post Consumer Carpet
  - Continuous Feeding and Product Collection System
  - Good Yields of Caprolactam and Mass Balance Achieved
  - Parameter Optimization Performed
- Condensed Products are Analyzed by GC/MS
  - Confirm Previous Results (90% in purity, 85% Yield)
- Estimated Production Costs are $.50/lb for Caprolactam Using a 100 millio lb/yr Plant as a Basis

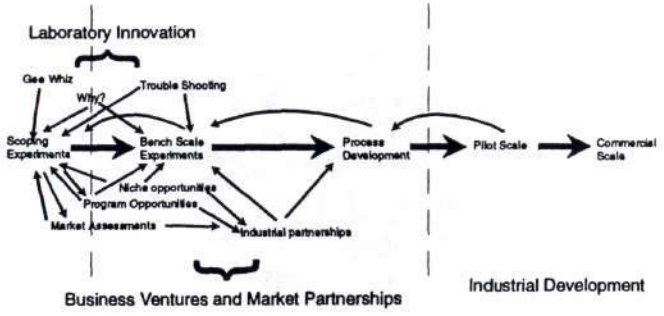
Recycling Nylon 6 from Waste Carpet



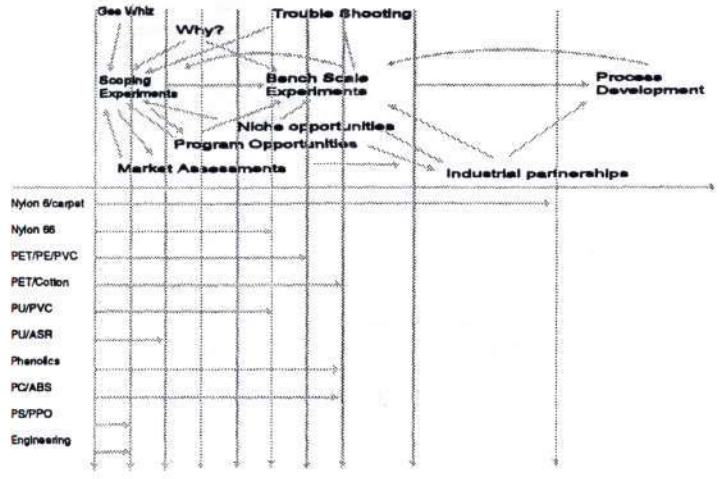
Flexible Chemical Processing Reactor Comparison

- Fluid Bed Reactor
  - Advantages
    - Temperature Control
  - Disadvantages
    - Residence Time Distribution
    - Catalyst/CaCO3 Separation
    - Gasification in Second Reactor
- Auger/Screw Reactor
  - Advantages
    - Plug Flow
    - Mechanical Mixing
    - Gasification in Same Reactor

Process Development Model



Process Development Status



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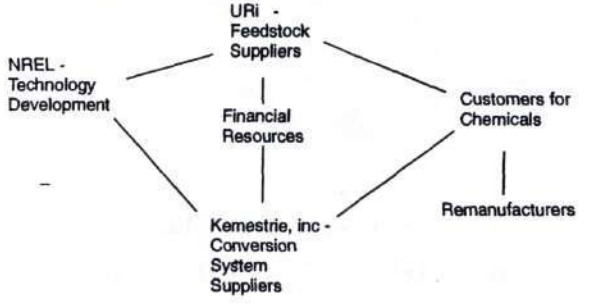
Flexible Chemical Processing Industrial Collaboration

- United Recycling inc Evaluating Process for Integration with National Carpet Collection Program:
- Kemestrie Inc to Demonstrate in Fluid Bed Facility:
  - Caprolactam Recovery
  - Residue Gasification
  - Product Purification
- Product Evaluation by Industry

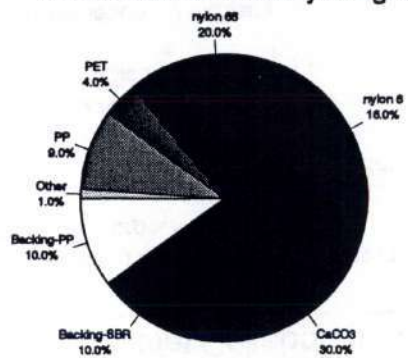
Flexible Chemical Processing Joint Development Project

- Complete Technology Development
- Demonstrate Performance
- Catalyze Partnership Formation



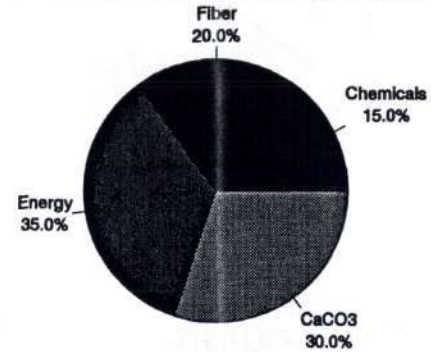
Integrated Carpet Recycling

Distribution of Feed by Weight



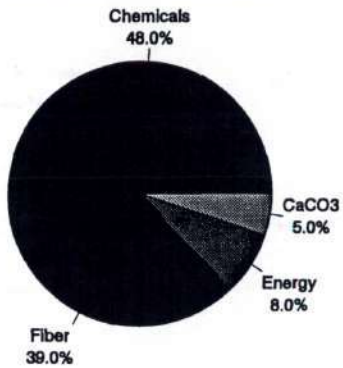
Integrated Carpet Recycling

Distribution of Products by Weight



Integrated Carpet Recycling

Distribution of Revenues



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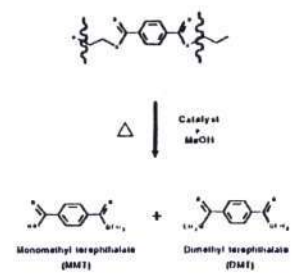
Flexible Chemical Processing
The Gasification Option

- Process Options:
  - Combustion
  - Partial Oxidation of Hydrocarbons to Carbon Monoxide, Hydrogen, Methane, etc.
  - Thermal Cracking to High BTU gases
- Energy Recovery:
  - Combustion and Steam Cycle - 20-25% Efficiency
  - Gasification and Gas Engine - 25-30%
  - Integrated Gasification, Combined Cycle 35-45%
  - gasification and Fuel Cell 45-50%
- Environmental Benefits:
  - Less Gas Emissions
  - Lower Temperature and More Control

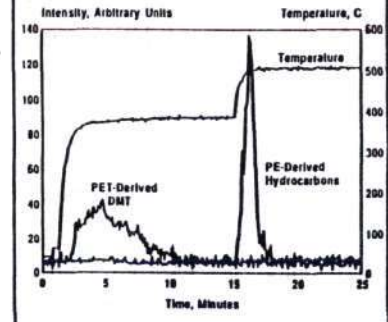
Flexible Chemical Processing
Current Lab Focus

- Expand Nylon -6 Work to Other Face Fiber Types
  - Co-processing
  - Block Operation
- Refine Gasification Technology for Relevant Feedstocks
- In-line Product Purification Process Development
- New Reactor Systems
- Cheaper Catalysts

PET to MMT and DMT



Temperature-Programmed Pyrolysis
PET and PE with Catalyst



PET/Cotton Textiles

- MBMS Studies Performed to Identfy Conditions to Recover the Monomer from PET in Presence of Cellulose
  - Minimal Formation of Cellulose Volatile Products
- Catalyst for PET Conversion also Catalyzes the Conversion of Cellulose to Char
- Char can be Gasified in Subsequent Step
- Issues:
  - Low Value of Chemical Product
  - Size of Plant that Results from Economics

Textiles in MSW, 1992

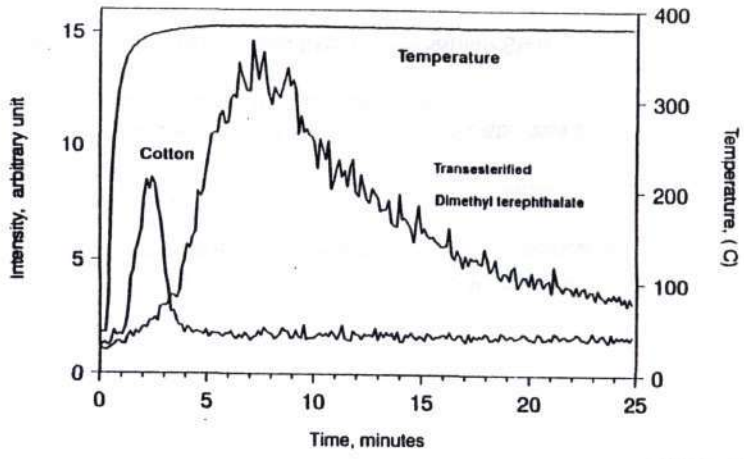
Product Category	Generation Thou tons	Recovery Thou tons	Recovery % of Generation	Discards Thou tons
Clothing/Footwear	3,514	176	5.0	3,338
Household Linens	1,137	57	5.0	1,080
Carpets	885	9	1.0	876
Tires	260	34	13.1	226
Furniture/Furnishings	740		neg.	740
Miscellaneous	208		neg.	208
Total Textiles	6,744	276	4.1	6,468

Neg. = Negligible

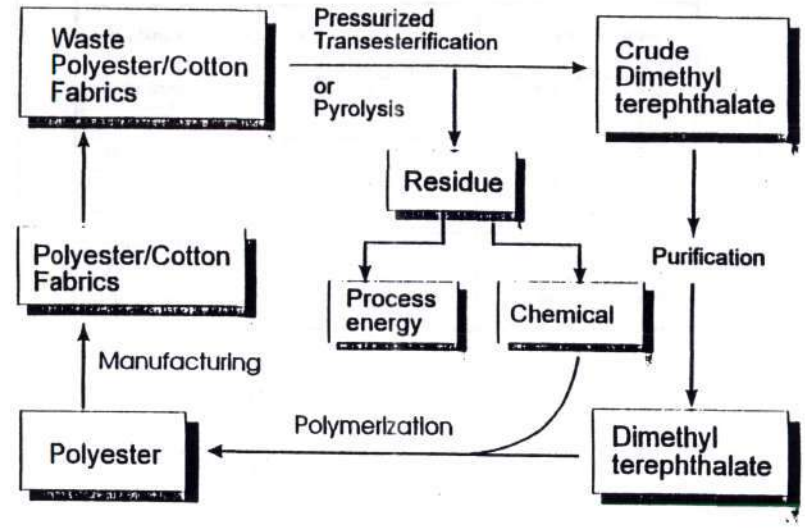
Source: Franklin Associates, Ltd.

Polyester Cloth

Isothermal/Methanol



Recycling Polyester from Polyester/Cotton Fabrics



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Polymer Recycling by Selective Pyrolysis Barriers to Success

- Feedstock Costs and Supply
- Technical Uncertainties
  - Conversion Performance
  - Product Value
- Product Quality
  - Variable Feed Composition
  - Conversion Impurities
- Return on Investment
  - Low Cost of Petroleum
  - Capital Investment Risk vs. Economy of Scale

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Flexible Chemical Processing Summary

- Integration of Caprolactam and Fiber Recovery
  - Smaller-Scale, Regional Operation
  - Energy Recovery From Residues by Gasification.
- Process Developments:
  - Alternative Reactor Design to be Tested
  - Simple Purification Process Developed
  - Use of Calcium Carbonate as Catalyst
- Recover Chemicals From PET in Textiles, etc:
  - Recovery of the PET monomer, DMT
  - Gasification of the cotton residue
  - Bench-Scale Work at NREL Continues